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Developing and Testing a Rough-Water Flexible Connector System for Pontoon Barges

William G. Hatch, Erick T. Huang, and Joseph L. Barthelemy
U.S. Naval Facilities Engineering Service Center
Port Hueneme, CA, USA

ABSTRACT

This paper presents the test results from a series of sea trials involving a new flexible connection system for joining multiple pontoon barges in elevated seaways. The tests were conducted to verify the performance of proposed rigging systems and operational procedures, and establish the credibility of the new flexible connector concept. The new connector and supporting methods of rigging and joining are designed to reduce and relieve the dynamic loads that occur as a result of relative motions and tug-induced forces. Information that is presented includes a description of the test the flexible connector system, description of test conditions and procedures, details of calibration, summary of results, and list of lessons learned.

KEYWORDS: Navy-Lightered (NL) pontoon, barge, causeway section, constant tension winch, flexible connector, separation force, pretension, in-line configuration, hip-tow configuration and modified in-line configuration.

BACKGROUND

Amphibious operations have been an integral part of the Navy's mission since World War II when pontoons played a significant role during invasions in both the Pacific and Mediterranean theatres. The basic pontoon structure has changed little during the past 50 years, and is comprised principally as a floating array of watertight, steel "cans" that are bolted together to form a completed barge structure as described in the Pontoon System Manual (1994). Amphibious structures made from Navy-Lightered (NL) pontoons include barge ferries, causeways and other floating platforms. However, size and construction limit the utility of the present NL system. Individual causeway sections, sized 27.4 m in length, 6.4 m in width, and 1.5 m in depth, must be transported aboard dedicated ships - ships that are being retired but not replaced by the Navy. The 1.5 m depth dimension limits cargo capacity to just 600 KN, while the effective cross-sectional area does not provide the inherent dynamic stability required for operating in waters above sea state 2 conditions.

The vision of the future amphibious operation sees a self-sustaining commercial containership transporting families of "building blocks" to an operational areas where these individual modules may be offloaded by existing container handling equipment and then assembled on the water as barges. The current research and development program at the Naval Facilities Engineering Service Center (NFESC) recommends the development of standard pontoon modules that are sized 12.2 m in length, 7.3 m in width, and 2.4 m in depth, a tradeoff between the requirements for shipping within standard container cells and the limitations of cargo handling and on-site assembly (Kane, 1996). Two types of connector are required to assemble floating structures at sea. A unit barge consists of three modules, joined end-to-end, using rigid-type connectors to fix articulation between mating faces, thereby producing a continuous-deck surface. After a number of such barges are assembled, they may be linked using flexible-type connectors to produce any of a number of useful floating platforms. Although NFESC is also developing the technology required to build the rigid module connector (Huang 1996 and 1997), it is the flexible connector used to join multiple barges that is the subject of this paper.

The primary operational objective in designing the flexible connector is to develop the capability to link multiple barges in elevated seaways through sea state 3 conditions, and to maneuver strings of barges in waves and swell on the open ocean up to sea state 5 conditions.

PROBLEM STATEMENT

A major deficiency typical of NL assets and modular pontoon structures in general is collision damage sustained by barges and the tugs that are supposed to be controlling them. Most connector related damage occurs as floating structures are joined on the water. After a proper connection is completed, the operational platform is generally stable against failure or damage under normal operating conditions. Making a flexible connection in calm seas is generally not hazardous because mating sections are easily controlled. However, in conditions of sea state 2 and above, surge and sway motions left unchecked can literally throw neighboring craft together. Existing standard operating procedures limit the execution of end-to-end connections to calmer waters whenever an unassisted marriage is attempted. The unassisted marriage is the method of choice by the NL crews because it is completed without the need for extraneous marriage bridle rigging. In the most basic sequence, two NL barges are maneuvered in close proximity head-to-head, and at the opportune moment, protruding male and female pipe shear connectors that link the two are "eased" into engagement. Variations on the basic theme include the use of overlapping barge hulls, ships or other physical means to help index and align the free ends of the sections as they are brought together. After the initial link is completed, and while under continued control by tender craft, Navy flexors are passed between barges and locked into position to secure the connections. Although the ability to complete an unassisted marriage has been proven on calmer waters, continued execution has resulted in repeated damage to hulls and connectors. The reinforced corners of the barges and the leading edges of the protruding pipe shear connectors are damaging and can easily open a hole in the thin skin of a pontoon. Both the execution time and safety hazards associated with this operation increase dramatically with building sea state, making the unassisted marriage an extreme liability in sea state 3 conditions.

NFESC CONCEPT

The NFESC concept is a connector system that provides the means to maintain proper alignment between mating barges as well as the control required to subdue erratic random motions as barges are drawn together. The system concept consists of a flexible connector proper, plus all hardware and rigging required to complete the connection. The primary benefits of the new connector are application in higher sea states, increased safety to personnel, reduced connecting times and less damage to the operational assets. The baseline concept is described by Huang (1995).

Aligning and Controlling

The concept connector system uses constant tension winches, marriage bridles, and elastomeric transitions that combine to bring mating barges together while progressively synchronizing their motions. Relative motions and snap loads are contained through effective tensioning, aligning and damping prior to final connector engagement, and dynamic stresses and moments are relieved as external loads are transferred to the connector body. In the sequence of events leading up to the linking of two barges, each section is taken under control by a tug. Each leg of a split-leg bridle harness is passed through an empty tunnel aboard the receiving barge and is connected to a flexible connector housed within the matching tunnel of the donating barge. As the winch-controlled bridle is drawn in to reduce the distance between barges, the two tender craft use opposing thrust to maintain a steady tension on the wire rope bridle legs. At the proper level of pretension, the approaching barges are held in proper alignment and the relative motions between sections begin to come into phase. Once the flexible alignment section of the connector enters the receiver tunnel, the ends of the barges are synchronized. In the event of sudden or dramatic surge motion, hazardous snap loads may be a threat. To minimize the possibility of this danger, NFESC is testing a constant tension winch that can overhaul the wire at a pre-determined load.

Flexible Connector Design

The flexible connector proper is comprised of linked leading and trailing heads, and two guillotine collars. When two causeway sections are connected, the leading head is locked by its guillotine within the tunnel of the receiving section, while the trailing head is locked by its guillotine within the tunnel of the donating section. A hinge pin joining the two heads is the link that allows articulation and translates all tensile and compressive loads into shear loads.

The flexible connector assembly consists of the flexible connector components just described, plus a guiding alignment member. The alignment member is the transitional element that guides the leading head into its receiving tunnel. The alignment member consists of a leader of high-strength chain encased within a compliant urethane sleeve of large cross-sectional area. The chain provides the strength required to resist the high tensile forces while the tapered urethane body allows smooth entry of the chain and prevents kinking as the connector is drawn into the receiving tunnel. The flexible connector system includes the flexible connector assembly plus the split-leg bridle harness and all other required rigging, wire rope, and hardware.

Figure 1 is a drawing of the flexible connector assembly (shown without the locking guillotines) that depicts the two heads, the shear pin, and the alignment member. Figure 2 pictures the closing moments of a marriage sequence as the flexible alignment member is drawn into its mating receiver tunnel.

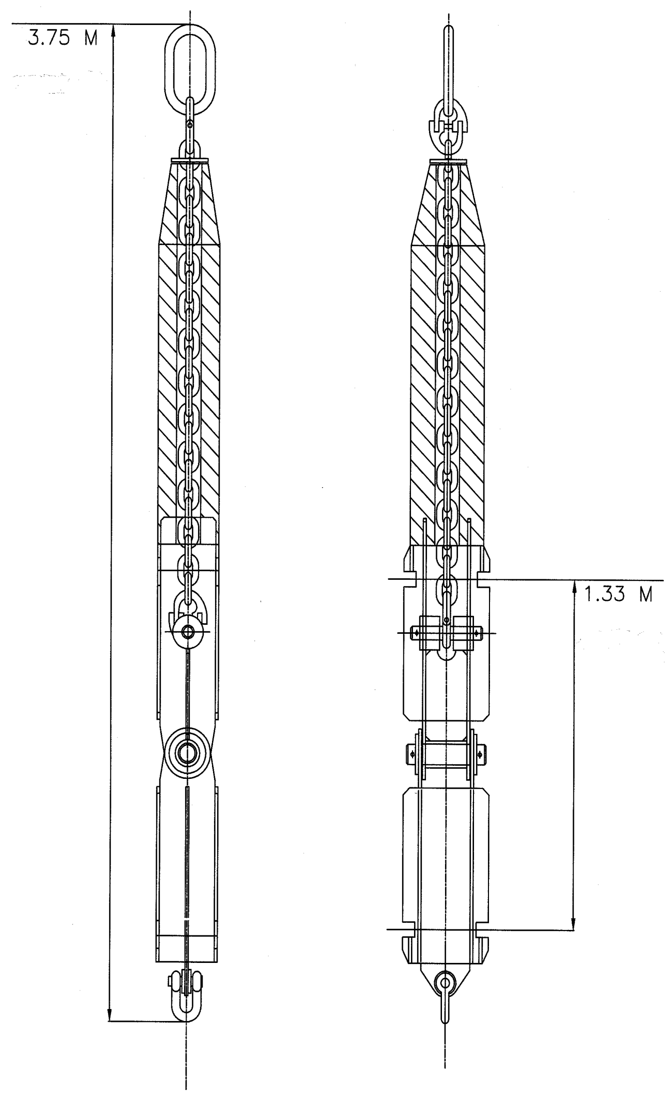

Figure 1. NFESC flexible connector assembly.

Figure 2. Entry of the alignment member during a marriage.

CONNECTOR TESTS

A series of demonstration tests was conducted using NL causeway sections as the test platforms, and prototypes of the NFESC flexible connector as the linking members. The tests were conducted at the Naval Amphibious Base, Coronado, California, using tugs and crews provided by Amphibious Construction Battalion One (ACB-1). The primary objectives were to verify performance of the connector and establish the most effective methods and equipment for operating under sea state 3 conditions.

Hardware and Setup

The test platforms consisted of two NL causeway sections that had the protruding NL pipe shear connectors at the ends removed. The platforms were reconfigured to accept the prototype connectors and upgraded to meet the requirements of the test plan. The ends were fitted with two different types of fender material to absorb impact energy during testing on the open seas.

Prototype connector. The prototype flexible connectors were fitted with special load indicating pins in place of the usual main hinge pin joining the two heads. The pin was designed to hinge the platforms while absorbing all tensile, compressive and shear forces to a maximum of 222.4 KN (50,000 lbs) per connector. The bi-axial gage configuration enabled the recording of the applied load vectors, and post processing produced the magnitude and direction of the resultant.

Rigging and winch. The split bridle legs were made from 1.9 cm wire rope. Two sizes of leg were used, 19.8 m and 27.4 m, to model, respectively, the connecting of two barges and multiple barges (with simulated cargo on deck). The primary operating winch used to draw lines was a pneumatic "air tugger", configured as a constant tension winch that provided line tensions as great as 44.5 KN (10,000 lbs) while operating in either the normal mode or the constant tension mode. In the later, the danger of snap loads was greatly reduced because the constant tension winch could overhaul or pay out when excessive forces were applied, or take up slack in the lines following sudden surge. The level of tension was controlled by air pressure regulated at the control console by the winch operator.

Instrumentation. In addition to the two load pins that replaced the connector hinge pins, load cells were installed at selected hard points and in-line in order to record the magnitude of applied line loads. The load cells were also used to monitor the marriage bridle loads and the bollard pull witnessed by the tugs. The analog output was recorded on a datalogger that displayed real time readings as it digitized and stored the information for subsequent downloading to a computer. The motions of the barges were monitored using a Humphreys SA07-0904-1 gyro-stabilized package that provided output data on roll, heave, surge, pitch, sway and yaw. A Datawell Wave Rider was deployed at the test site to provide local information on wave height and period that was recorded on the datalogger.

Test Parameters

The tests were conducted according to a matrix of physical and environmental variables. The parameters that were used to make up the test matrix were as follow:

Arrangement of barge and tug. Several different arrangements of barge and controlling tug were tried in order to evaluate the effects of attachment point and position. In the "in-line" configuration shown in Figure 3, each tug was attached behind its respective barge (or string) to form a continuous line. In the "hip-tow" approach shown in Figure 4, each tug was tied alongside its respective barge. A modified in-line arrangement used a barge/tug combination on a hip-tow configuration followed by a barge/tug in-line. The modified in-line configuration is shown in Figure 5. A final configuration required the use of a single tug tied alongside the lead barge.

Level of pretension. The level of pretension - that is, the force of separation maintained on the lines between approaching barges, was another variable. In addition to changing the magnitude of pretension, several methods of developing the force of separation were tried, including two tugs engaged in opposing thrust, a single tug pulling against an anchor, and the exploitation of hydrodynamic drag that occurs naturally as a barge is taken under tow.

Rate of closure. The speed of the winch was varied to the maximum level allowed by the separation force. The overhaul point of the constant tension winch was adjusted as the separation force varied.

Sea Conditions. Although the physical state of the seas was not a factor that could be controlled, a cross-section of local conditions was achieved by testing in areas ranging from dockside in protected harbors, to the open ocean 2 miles offshore, and by testing during winter and early spring when the desired sea state 3 conditions could be approached gradually by changing the location of the test site. Connector tests were conducted with the array of barges and tugs headed into the seaway, traveling parallel to the waves, and rotating through 180 degrees.

Calibration and Pilot Tests

The initial sequence of tests was conducted in the protected bay to establish procedures and train the crew. All efforts to prepare instrumentation were conducted under calm conditions, including the verification of deck fixture integrity and winch capability, calibration and comparison of load cell data, and measuring of tug thrust capability. Each of the test options was completed first in calm water areas to identify potential problems or hazards before journeying into the open ocean.

Thrust and load cell calibration. Initial tests were conducted to establish the level of thrust force that could be produced by the supporting tugs, and at the same time calibrate in place the connector load pins to at least 44.5 KN. In order to acquire useful data for the power curve, engine speed was stepped up for short intervals to 2,000 RPM, even though normal operating procedures do not allow speeds in excess of 1800 RPM. Data values were used to establish bollard pull as a function of engine speed, with thrust values ranging from 10.7 KN at idle to 48 KN with both engines revved to 2,000 RPM.

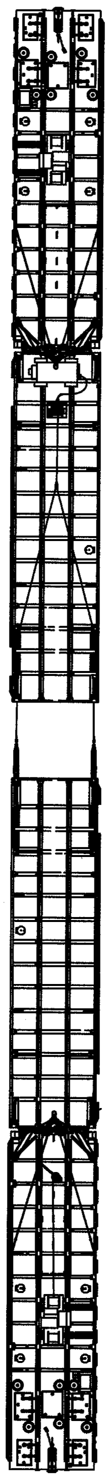

Figure 3. In-line Configuration.

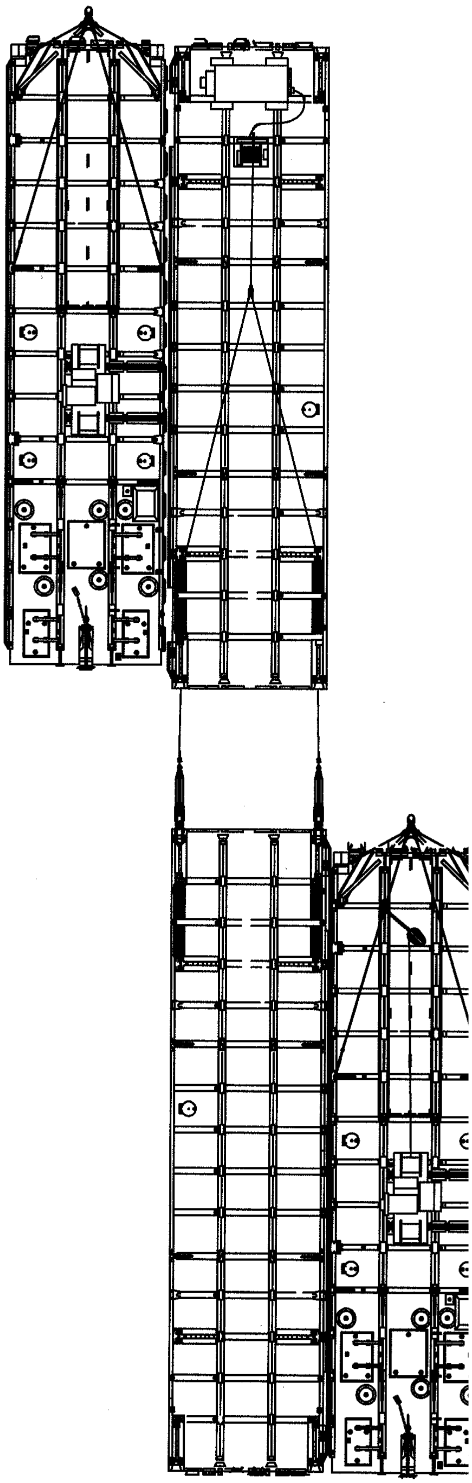

Figure 4. Hip-tow configuration.

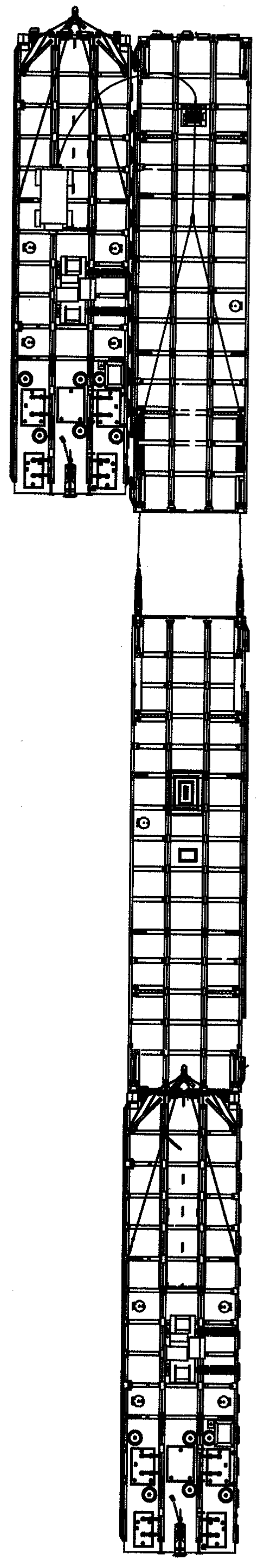

Figure 5. Modified in-line.

Winch pull. Tests were conducted to ensure that the pull of the winch could not exceed the safe load limits of the deck fittings. Load cells were placed between each snatch block and padeye, and a third load cell was positioned at the junction of the winch cable and the two split-leg marriage bridles. The tests demonstrated that the 84.5 KN pull of the winch did not produce more than 133.4 KN of force or exceed a 30 degree angle on the fittings. Levels were within the 4:1 safety factor applied to wire and rigging gear. Figure 6 is a typical data plot of load and pressure recorded during operation of the constant tension winch.

Ocean Tests

Sea conditions encountered during the periods of testing were unseasonably calm. Calm water tests benefited from still air and glassy water found in the protected areas of San Diego Bay, but the open ocean two miles west of Point Loma produced only a 1.3 m, 10 second swell with decaying waves. The ambient sea state did produce some significant load spikes in the connector pins when barges were connected as shown in Figure 7, but wave conditions were not sufficiently dynamic to properly test the constant tension winch during actual marriages of barges. The forces witnessed by the connector pins were of very short duration, whereas the constant tension winch is designed to overhaul and payout in response to loads applied over a longer interval of time. Open ocean tests were conducted with barge/ tugs in the hip-tow and in-line configurations.

Hip-tow configuration. Several connector tests were completed with barge and tug attached in hip tow configuration, the method favored by experienced NL crews to complete unassisted marriages on calm water. When this technique is used, there is a marked tendency for the trailing section to yaw and sway while being drawn toward the leading section, especially in calm waters and when working under low levels of line pretension. When connectors do not enter receivers smoothly on the first attempt, there is a tendency to overshoot, with momentum of the trailing barge being transferred to the lead barge through contact. Forces are intermittently upset by the application and removal of forces from the constant tension winch as the operator draws the line. The hip-tow configuration effectively produces a moment couple on the towed barges as the natural result of eccentric thrust and drag forces. Trials conducted in both calm water and open seas verified that connections could be made more quickly and with greater ease at higher levels of pretension force, even though a higher rotational speed was produced by the eccentricity of drag and thrust. Release of the guillotine mechanism used to lock and unlock connectors, causeway separation and subsequent marriage became routine accomplishments, with connections completed at higher levels of pretension being more positive and controllable than those made at lower levels. At 1200 - 1500 RPM, tugs produced the favorable 26.7 KN of pretension required for marriage. Although rotation caused by eccentric thrust and drag was unavoidable, it did not present a problem and was ignored whenever there was adequate room to maneuver and favorable seas were encountered. When sea or swell became dangerous at certain angles of attack, the deck operation was suspended until the window had passed.

In-line configuration. Barges and tugs were configured for in-line testing. It was anticipated that increased control would be afforded by keeping forces due to thrust and drag in line. Tugs were operated using the opposing thrust produced at 1200 - 1800 RPM engine speed to maintain pretension forces while the winch drew sections together. The in-line configuration proved to be a more controllable arrangement of barge and tug as it was possible to attain high separation forces with winch loads confined to the middle of the efficiency band of the constant tension winch where control sensitivity is good. There were no observable lateral movements between converging sections the tendency to overshoot receivers was dramatically reduced. During some of the repetitions, the operation was actually predictable and uneventful.

Modified in-line configuration. Although the in-line configuration does provide the most positive control, it requires more time to set up (two additional end-to-end matings) and potentially exposes the stern of one of the tugs to the seas. The compromise shown in Figure 5 places one tug in a hip tow with the lead barge while the trailing barge is connected in-line with a tug. This places the most maneuverable craft in the stern with good visibility for alignment control and allows both tugs to be steaming in the same direction.

LESSONS LEARNED

The primary objective of the sea trials conducted by NFESC was to demonstrate a new flexible connector technology for linking multiple barges on the open seas - a technology that included a prototype flexible connector, a constant tension winch, and novel operational procedures. The test matrix was designed to: (1) establish the effectiveness of various techniques in aligning and controlling barges as they are married in sea state 3 conditions. (2) verify the performance characteristics of a prototype flexible connector that retains the strength and integrity of the existing Navy flexor, but eliminates the dangers of protruding male and female pipe shear connectors at the end face of a causeway section; (3) demonstrate the ability of a constant tension winch to reduce the level of loads in marriage bridle lines caused by surge, sway and other random barge motions. Although weather conditions and sea states prevailing during periods of testing seldom matched the ideal environment called out in the test plan, the experience gained and information collected have been highly insightful. The following are observations and recommendations stemming from the experience.

Flexible Connector

The prototype flexible connector performs well and the concept shows great promise as a sea state 3 connecting system. A general recommendation is that the leading and trailing heads should be made from a quality cast material rather than as a welded fabrication. The hinge pin should be designed to provide durable, low maintenance service. The flexible connector system requires additional development to dampen the high dynamic shock loads that are transferred through the hinge pin, and to compensate for loads imposed by yaw and lateral shear. The benefits of improved safety and greater damage control derived from the smooth fendered ends of barges using the new connector system offer payoffs that make the continued effort well worthwhile.

Constant Tension Winch

The constant tension winch performs well, although the overhaul and constant tension features were not fully demonstrated because the lower-than-expected sea states did not offer an adequate operational challenge to the system. The 44.5 KN capacity of the winch is adequate for connections completed on seaways up to sea state 3. Operator intervention is necessary during the final moments of connection when it is often necessary to stop and synchronize the pull of the winch with the motion of the mating platforms. The calm water and at-sea tests did reinforce the belief that a constant tension winch could be a valuable asset in controlling the magnitude of loads imposed on the wire bridle system. A properly balanced winch/wire combination will provide safer, more controllable connections in significantly less time than current procedures permit.

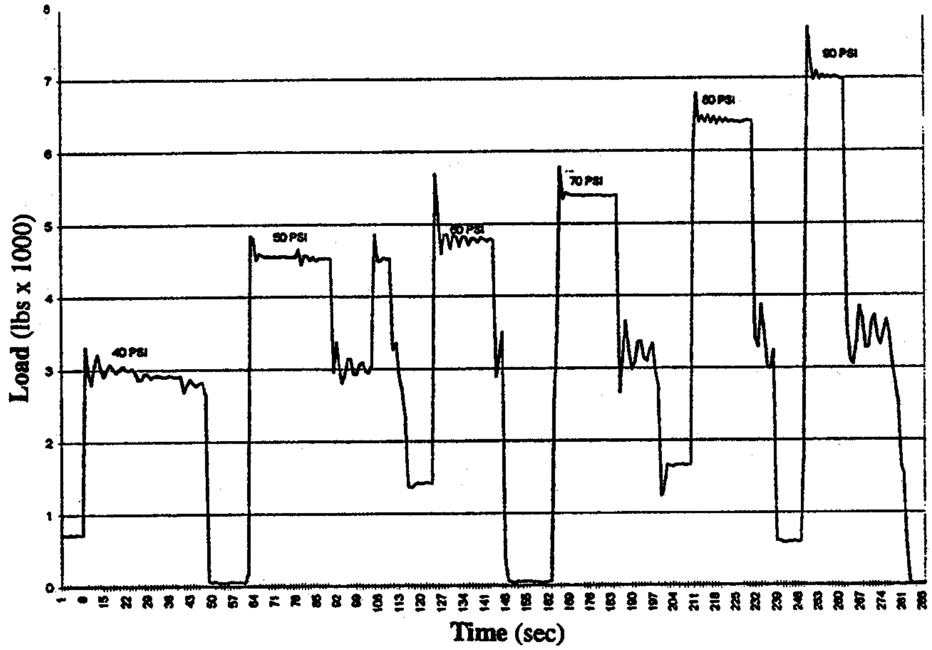

Figure 6. Typical plot of constant tension winch load as a function of control pressure.

multiply	by	to obtain
psi	6.8947	kilopascals
lbs	4.4482	newtons

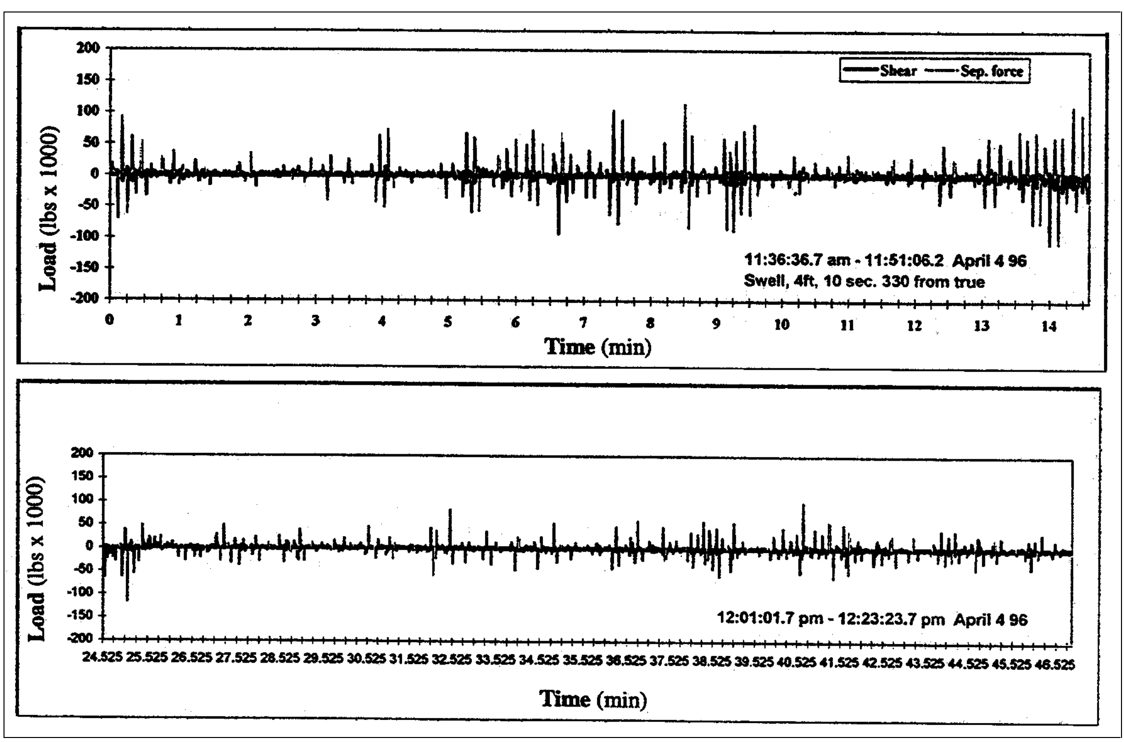

Figure 7. Forces recorded at the connector shear pin over time.

Rigging and Configuration

When one or both of the escort tugs is tied alongside in a hip tow configuration, the matrix of tugs and barges will rotate when taken under tow. The amount of rotation is a function of the magnitude of thrust and the level of line tension maintained by the winch. Operators should allow the tow to rotate, completing connections as expeditiously as possible. Keeping tugs in line with the barges, however, provides superior control when using marriage bridles between sections. The in-line method is not always practical, however, because many extraneous factors can affect the availability of connecting points between the tugs and the barges that they are trying to connect. The modified in-line configuration is a useful compromise that allows both tugs to maintain the same heading, but produces less of a rotational moment than occurs in the hip-tow method. The modified configuration permits reasonably rapid connection of successive barges to produce a causeway string and proved to be the method of choice by operating personnel. In all marriages, the level of pretension on the bridle lines must be maintained high enough to maintain alignment of the barges. Low separation forces result in excessive yaw and sway motions as the barges are drawn toward marriage. Deck fittings, sheaves and fairleads need to be certifiable and placed in locations that minimize bridle wear or entanglement. Bridles are suitable for multiple connection operations, but must be inspected and maintained regularly.

CLOSING

The market potential for a novel at-sea flexible connector that is safe, effective and easy to use extends far beyond the military sector. Navy lighters offer but one configuration of pontoon assets world wide. The spin-off of technology to maritime commerce is more than a likely consequence since there are many types of barge systems and floating applications within the commercial market. Currently, commercially used flexible connecting systems are limited almost exclusively to inland waters where surface wave conditions are subdued. The NFESC alternative for linking barges at sea opens a potential window of opportunity to over-water commerce and transportation.

ACKNOWLEDGEMENTS

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